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1 Goal of Research:

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This objective required several innovations:

(1) Conventional gyros are excited cw with radiation of short coherence time. The gyro must be pulse-excited. The reason for pulse excitation derives from the ultimate objective of using squeezed radiation for the improvement of gyro performance. Squeezing requires pulse excitation of high peak intensity.
(2) Development of laser sources that are of particularly low noise and that have repetition rates of 1GHz or higher. The high repetition rate is required for the suppression of Guided Acoustic Wave Brillouin Scattering.
(3) Study and development of a new orthogonal polarization gyro suitable for injection of squeezed vacuum.

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Final Report for the Office of Naval Research
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"Pulse Excited Fiber Gyro"
Project Period: June 1, 1995 – May 31, 1998

Staff:

Prof. H.A. Haus, Principal Investigator; Shu Namiki, visiting scientist; Patrick Chou, graduate student; Ravindra Dalal, undergraduate UROP student

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Summary of Accomplishments

1. The pulse excitation of fiber gyros has been demonstrated. The coherence time of the pulses is shorter than that of ASE sources. The adverse effects of the fiber nonlinearity have been eliminated with pulse stretching via dispersive propagation.[1]

2. The stretched pulse laser source developed from previous MIT designs has been demonstrated to have exceptionally low noise. The level of the noise is consistent with theoretical calculations that explain the noise as caused solely by quantum effects for integration times of the order of 0.1 sec and shorter.[2,3]

3. The orthogonal polarization gyro has been studied extensively theoretically. It was found that it is not "reciprocal" in the same sense as the Y-coupled Sagnac-loop gyro. An orthogonal polarization gyro has been constructed at Draper. Draper Laboratory is funding the continued research on this gyro.

The work on these four issues is detailed below.

1. Pulse Excited Fiber Gyro

Over the past two years we have been working with Draper Laboratory on the pulse-excited gyro project. Our interest in a pulse-excited gyro hinged on the need for the use of pulses in the squeezing process in fibers to achieve the required high peak intensities. If squeezed radiation is to be used to improve the sensitivity of fiber gyros, it is necessary to operate fiber gyros under pulsed excitation. Draper's interest in the project grew when it was realized that the use of coherent radiation offered new opportunities for the control of the radiation and the processing of the rotation signal. A pulsed coherent source can achieve short coherence lengths (<100 □) at higher power levels than is possible with amplified spontaneous emission, as currently used. Further, the carrier frequency of a coherent modelocked laser can be locked to a reference, whereas the center frequency of a spontaneous emission spectrum cannot be similarly controlled.

Thus far, it was demonstrated by Patrick Chou, the graduate student working on the project, that dispersion via propagation through a fiber of the pulse generated in our stretched pulse laser can produce quasi-cw broadband radiation. Excitation of the gyro with this broadband, quasi-cw radiation produces the same signal to noise ratio as realized with amplified spontaneous emission of the same power and bandwidth.[1] Direct pulse excitation, without dispersion, however, leads to nonlinear effects due to imperfect 50/50 splitting at the input coupler, already well described by Ezekiel et al.[4]. When squeezed radiation is used, the probe beam, also alternating as the squeezing pump, cannot be dispersed, since phase coherence with the squeezed vacuum could not be maintained under these conditions. Hence, in order to use squeezed vacuum to improve the sensitivity of the gyro, the gyro must be directly pulse excited. As of now, we do not know whether the beam splitter can be improved sufficiently to suppress the nonlinear effects in the gyro. In pursuing the work, we are supplied by Draper Laboratory with state of the art gyros. The support of the work on pulse excited fiber gyros has been taken over by Draper Laboratory, where the effort is being continued by the graduate student Patrick Chou. Appendix I is a copy of the work outline submitted to Draper Laboratory. Appendix II is a more detailed account than the one presented at CLEO-IQEC 1998.

2. Development of new laser sources

Fiber systems are the most convenient sources for the generation and use of squeezed radiation: (a) problems of spatial mode conversion and control do not arise. (b) propagation losses and coupling losses are small (c) large nonlinear phase shifts can be produced within distances of negligible loss. Hence the pump lasers and local oscillator lasers are also, most conveniently, fiber lasers. We have developed a low noise, high energy fiber ring laser with considerable success, as part of the source development aimed at the generation of squeezed radiation.

We have measured, and compared with theory, the noise of mode-locked all-fiber ring lasers. We have demonstrated that the timing jitter of these lasers (0.54 ps in 0.1 sec) is due solely to quantum effects, i.e. the spontaneous emission of the gain medium[2,3]. These results were obtained on a soliton fiber ring laser with one single circulating pulse. In the generation of squeezed light in a Sagnac fiber ring, pulse repetition rates must be of the order of 1 GHz or higher, in order to prevent Guided Acoustic Wave Brillouin Scattering noise from entering the detection spectral window. Thus harmonically modelocked fiber-ring lasers have to be developed for this purpose. We have successfully operated a harmonically modelocked laser at 1 GHz repetition rate with an average power of 20 mW and peak intensity of 40 W sufficient to achieve 1.5 □ phase shifts in a Sagnac fiber loop of 200 m length. This laser also showed very small timing jitter. Incidentally, we are currently engaged in a joint experiment with Lincoln Laboratory to take advantage of this extraordinarily small timing jitter. The purpose of the experiment is to provide digital time delays for sampling scopes and/or other diagnostic equipment that requires the setting of precisely controlled time delays. Long time delays generated electronically become less and less accurate the longer the delay. A harmonically modelocked fiber ring laser will provide the long term time delays, the added shorter time intervals are to be generated electronically.

In recent work, we have attacked the quantum theory of noise in modelocked lasers. The analysis is fully quantum mechanical; the only approximation made is the assumption that the signal part is much larger than the quantum noise. It is an extension of the semi-classical analysis of noise in modelocked lasers previously published by Haus and Mecozzi.[4] The minimum amount of noise generated by the components in the laser is determined from the requirement that the in-phase and quadrature components of the wave emitted by the laser into free space obey the proper commutation relation. The paper is currently being prepared for submission to *JOSA B*. In further work under another ONR grant, we hope to check experimentally the degree to which actual lasers operate near the quantum limit.

3. Study and Development of a New Orthogonal Polarization Gyro

The minimum configuration, Y-coupled Sagnac loop fiber gyro uses the same port for both input and output. A fiber gyro that uses squeezed vacuum for shot noise suppression requires two input ports, one for the probe and one for the squeezed vacuum. A gyro for this use was conceived and first demonstrated at MIT by C.R Doerr, then a graduate student.[6] Its schematic is shown in Fig. 1. The two inputs to the gyro are supplied through a beam splitter with P polarization for the probe, S-polarization for the squeezed vacuum into the beam splitter marked PBS, following the SPBS beam splitter (SPBS stands for special polarization beam splitter indicating that the splitting is not perfect, allowing some of the pump to be reused as local oscillator).

The pulses must be either incoherent or made incoherent with an asynchronous (to the pulse train) or randomly-driven phase modulator before entering the system in order to suppress noise due to reflections. However, the necessity of this step remains to be determined experimentally.

The light must be quadrature squeezed, which can be accomplished stably with the self-phase-stabilized squeezer. The relative phase between the LO and squeezed vacuum from the squeezer must be appropriately adjusted for minimum noise via a wave plate. The LO and squeezed vacuum must then be injected into an OPFOG using a polarization-independent circulator.

The pulses must be dispersed before entering the gyroscope fiber coil so as to reduce the nonlinearity in the gyroscope. Note that the nonlinearity drift problem in the squeezer is not too severe because of the phase adjustment for the squeezed vacuum. Both the squeezed vacuum and LO must be dispersed while maintaining their relative phase. The simplest way to do this, with some sacrifice in noise, is to place the dispersion inside the gyroscope (use positive dispersion fiber in the spatial-filter fiber and the fiber ring). If the dispersion is accomplished inside the sensor rather than before it, a birefringent plate placed before the spatial-filter fiber and with its birefringence axes aligned with those of the spatial-filter fiber can eliminate the problem of nonlinear cross-phase modulation when the pulses initially enter the spatial filter. This is because the short pulses separate in the birefringent plate before entering the spatial-filter fiber.

Finally, the light enters a balanced detection apparatus. In principle, when there is no rotation of the gyroscope, the gyroscope output has very little noise.

We have studied the ways in which the performance of such a gyro coincides with and/or differs from the performance of a minimal configuration gyro. The latter is a so called reciprocal configuration in which a 50/50 beam splitter exciting the Sagnac loop retains an ideal performance, even if the beam splitter has small loss as expected. The orthogonal polarization gyro is not "reciprocal" in the same way. We have studied means for elimination of this offset . These ideas will be tested on a setup, which is now under construction at Draper Laboratories and will serve as Master's thesis for the student Melody Lynch.

Honors:

Prof. Haus received the President's 1995 National Science Medal, and the Ludwig Wittgenstein Prize 1997 of the Österreichische Forschungsgemeinschaft.

Publications Listing Grant Support

1. P. C. Chou, H. A. Haus, and O. M. Laznicka, "Pulse excited interferometric fiber-optic gyroscope," Technical Digest, Conference on Lasers and Electro-Optics (CLEO'98), San Francisco, CA May 3-8, 1998, paper CWR5, p.313.
2. S. Namiki and H. A. Haus, "Noise of the stretched pulse fiber laser: Part I—Theory," IEEE Journal of Quantum Electronics 33, 649-659, May 1997.
3. C. X. Yu, S. Namiki, and H. A. Haus, "Noise of the stretched pulse fiber laser: Part II—Experiments," IEEE Journal of Quantum Electronics 33, 660-668, May 19997.
4. H. A. Haus and M. Margalit, "Quantum noise of modelocked lasers," to be submitted to JOSA B.

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4. S. Ezekiel and H. J. Arditty, Fiber-Optic Rotation Sensors and Related Technol. 2-26(1982).
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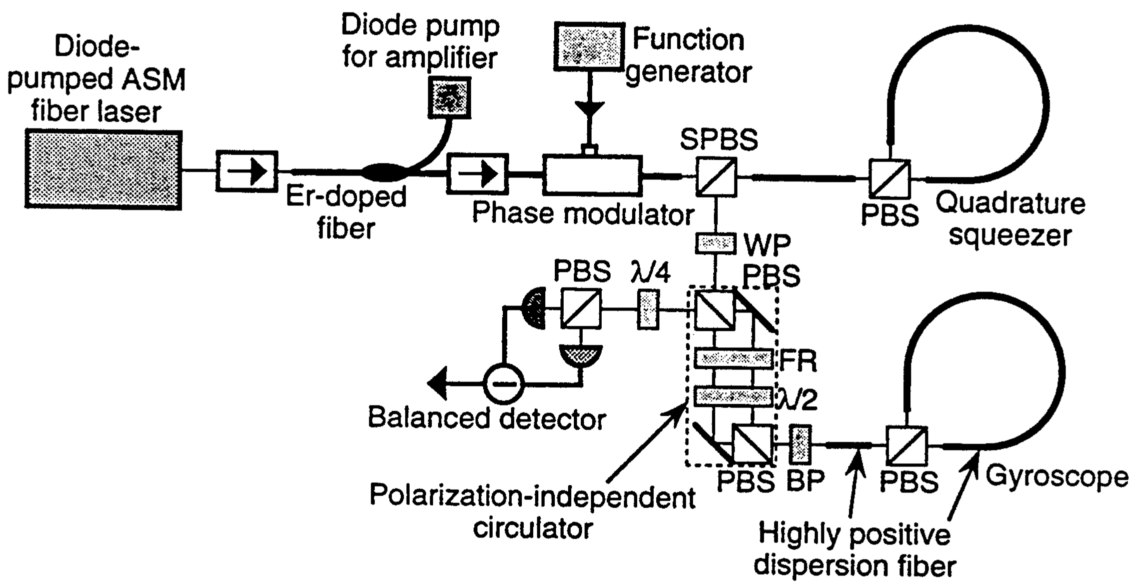

Figure 1: A quadrature-squeezed OPFG: a nearly noiseless fiber optic gyroscope. WP = wave plate, BP = birefringent plate, FR = Faraday rotator, $\lambda/2$ = half-wave plate, $\lambda/4$ = quarter-wave plate.

Appendix I

Ultra-Stable IFOG Scale Factor and Bias Drift Using an Optical Source with Stabilized Wavelength and Ultra-Low Coherence

In previous CSDL funded research at MIT, Professor Haus's group pursued the use of short soliton pulses in fiber gyros, both interferometric and resonant. In the context of this work, the pulses offered advantages such as the ability to employ the quantum noise reduction technique "optical squeezing" and also smaller coherent backscattering errors due to the short interaction length of counter-propagating pulses in the gyro coil. Experimental demonstration of these goals proved to be quite challenging, and work in this area continues at MIT by means of other funding agencies.

In the High Performance Fiber Optic Gyroscopic Laboratory here at CSDL, we are working on the technology necessary for an optical source which can provide a quantum leap in IFOG performance. There is a clear distinction between our project and the one described above. Although we use short pulses as well, we use them not in the sensor itself, but as a means of generating a wavelength stabilized optical source with ultra-low coherence.

For the past year we have been doing unfunded research which has demonstrated a wide bandwidth continuous wave source that consists of a short pulse Additive-Pulse Modelocked (APM) fiber laser and a pulse stretcher. The APM fiber laser is chosen because of its low noise characteristics. By taking advantage of the high nonlinearity due to short pulses, we can achieve coherence and stability which surpass those of currently proposed superluminescent diode (SLD) and erbium fluorescence sources by at least an order of magnitude. This is necessary for strategic IFOG performance which requires ultra-low coherence and stable spectral mean of 0.01 ppm.

To realize this source, we must develop the following technologies:

- Supercontinuum generation. This is the nonlinear mechanism which provides the enormous optical bandwidth necessary for low backscattering error. A bandwidth of >1 μm has been reported in the literature.
- Wavelength stabilization of APM fiber laser. Because SLD's and erbium fluorescence sources are incoherent by nature, their wavelength stabilization is difficult. An APM fiber laser, however, is a broadband source which can be injection locked to provide a highly stable mean wavelength, which ensures a highly accurate scale factor.
- Environmentally stable APM fiber laser. For practical applications, the pulsed operation of an APM fiber laser must be made impervious to environmental fluctuations. Commercial APM fiber lasers are thermally and mechanically insulated.

We can redesign the laser to make it inherently robust, thus relaxing expensive and space consuming packaging requirements.

- Pulse stretching via fiber grating. An essential component of the source is the pulse stretcher, which converts pulses into coherent continuous wave light by broadening the pulses in time. This device can be a highly dispersive medium such as a dispersion compensating fiber grating. Such gratings are beginning to emerge due to a push by long haul fiber telecommunications research, but we will likely have to develop custom gratings in order to provide enough dispersion.

A schedule for project development is attached.

This effort attacks fundamental issues and could serve well as a source of thesis projects for a number of MIT students in Electrical Engineering. The wavelength stabilization and the environmentally stable APM fiber laser could each constitute an entire thesis by themselves. For my own topic, I would like to concentrate on the supercontinuum generation, the pulse stretching, and the IFOG noise characteristics associated with this optical source.

These exciting new technologies are essential for the next tier of IFOG performance and can be applied toward other sensors as well. We look forward to their successful development at CSDL.

Patrick C. Chou
March 20, 1997

Appendix II

Pulse and Pseudo-CW Excitation of an Interferometric Fiber Optical Gyroscope (IFOG)

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ABSTRACT

We demonstrate the operation of an IFOG which uses an Additive-Pulse Modelocked (APM) fiber laser as an optical source. Fiber lasers of this type are promising candidates for use in high performance IFOGs because of their low noise, wide optical bandwidth, and potential for highly stable mean wavelength. Rotation signal errors due to the Kerr nonlinearity are shown.

Introduction

In fiber optic gyroscopes, an incoherent CW optical source is essential in order to avoid errors due to coherent backscattering[1] and the Kerr effect[2]. Currently, the sources of choice are the superluminescent diode and Erbium fiber ASE. They are chosen because of their wide optical bandwidths at relatively high powers.

An APM fiber laser can provide wide optical bandwidth as well, but it has not been previously considered as an optical source for fiber optic gyroscopes because of its pulsed output. The reason is that the high peak powers of the short pulses can give rise to severe rotation rate errors via the Kerr effect in the gyro coil.

However, in this memo we show that pulses can be converted into quasi-CW radiation, while still retaining the wide bandwidth and can thus serve as a pseudo-CW incoherent source. The APM fiber laser is a prime candidate because of its low excess noise and ability to maintain broad bandwidth at high output power.

2. Experiment and Results

The demonstration of a pulse and pseudo-CW excited IFOG was carried out at Draper Laboratories, where the gyro coil and much of the supporting electronics was already configured. A diagram of the experimental setup is shown in Figure 1. The region

enclosed by the dashed lines is the standard IFOG minimum configuration[3] without an optical source. This particular version uses a 1 km coil of quadrupolar wound Fujikura Panda fiber, a UTP integrated Y-branch and phase modulator on polarizing lithium niobate waveguides, and a fused 3dB PM fiber coupler. The optical source consists of an APM fiber laser with an external EDFA at the output. The EDFA can also serve as an ASE source when it receives no input signal. A 99/1 tap coupler is used for monitoring the optical spectrum, and the normally unused port of the 50/50 coupler is connected to a fast detector and oscilloscope to help monitor whether the APM laser is pulsing or not.

At the output of the EDFA we can insert a 25.2 km spool of Corning SMF28 fiber to provide approximately 540 ps/nm of dispersion. This is used for stretching the pulses so that the inverse pulse width is nearly comparable to the repetition rate, thus converting the pulsed light into pseudo-CW light with the same optical power spectrum.

Results are given for cases in which three different sources were used: 1) EDFA ASE, 2) Pulses amplified by the EDFA, and 3) Pulses amplified and then stretched. In the comparisons of these cases, care was taken to ensure that all average powers are identical.

Figure 2 shows measured phase error as a function of input power. There is enormous power dependent error when pulse excited, and no noticeable dependence when ASE is used. This power dependence indicates that it is due to the Kerr nonlinearity. The stretched pulses show some power dependence, indicating that it does not exactly resemble CW light. An additional factor of 10 in the source bandwidth or in the total dispersion would make this source indistinguishable from a truly incoherent one.

1. Future Directions and Conclusions

In future work, we can take advantage of the APM fiber laser in two ways. First, we can use the high nonlinearity in the pulse peak powers to generate supercontinuum, which can enable us to attain optical bandwidths of at least 100 nm[4]. Second, we can make use of the fact that the APM laser is a coherent source which can be injection locked and thus wavelength stabilized. The mean wavelength stability is crucial to the scale factor accuracy of IFOGs and is currently limiting their performance.

The 25.2 km of fiber may be disturbing to anyone concerned with compactness for packaging. However, suitable dispersion compensating fiber gratings that are now available can easily replace the long fiber. The wide bandwidth of the supercontinuum can also reduce the amount of dispersion necessary.

In summary, we demonstrate that while blindly replacing an IFOG's broadband CW source with an ultrashort pulse source causes the expected problems with Kerr effect, we can take simple steps to alleviate the problem. Additionally, switching to a pulse source makes techniques accessible thtat will enable us to reach the next tier in IFOG performance.

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[1] Bohm, P. Russer, E. Weidel, and R. Ulrich, "Low-Noise Fiber-Optic Gyroscope," *Optics Letters*, vol. 6, p. 64-6, 1981.

[2] A. E. Kaplan and P. Meystre, "Large Enhancement of the Sagnac Effect in a Nonlinear Ring Resonator and Related Effects," Springer Series in Optical Sciences, vol. 32, p. 375-85, 1982.

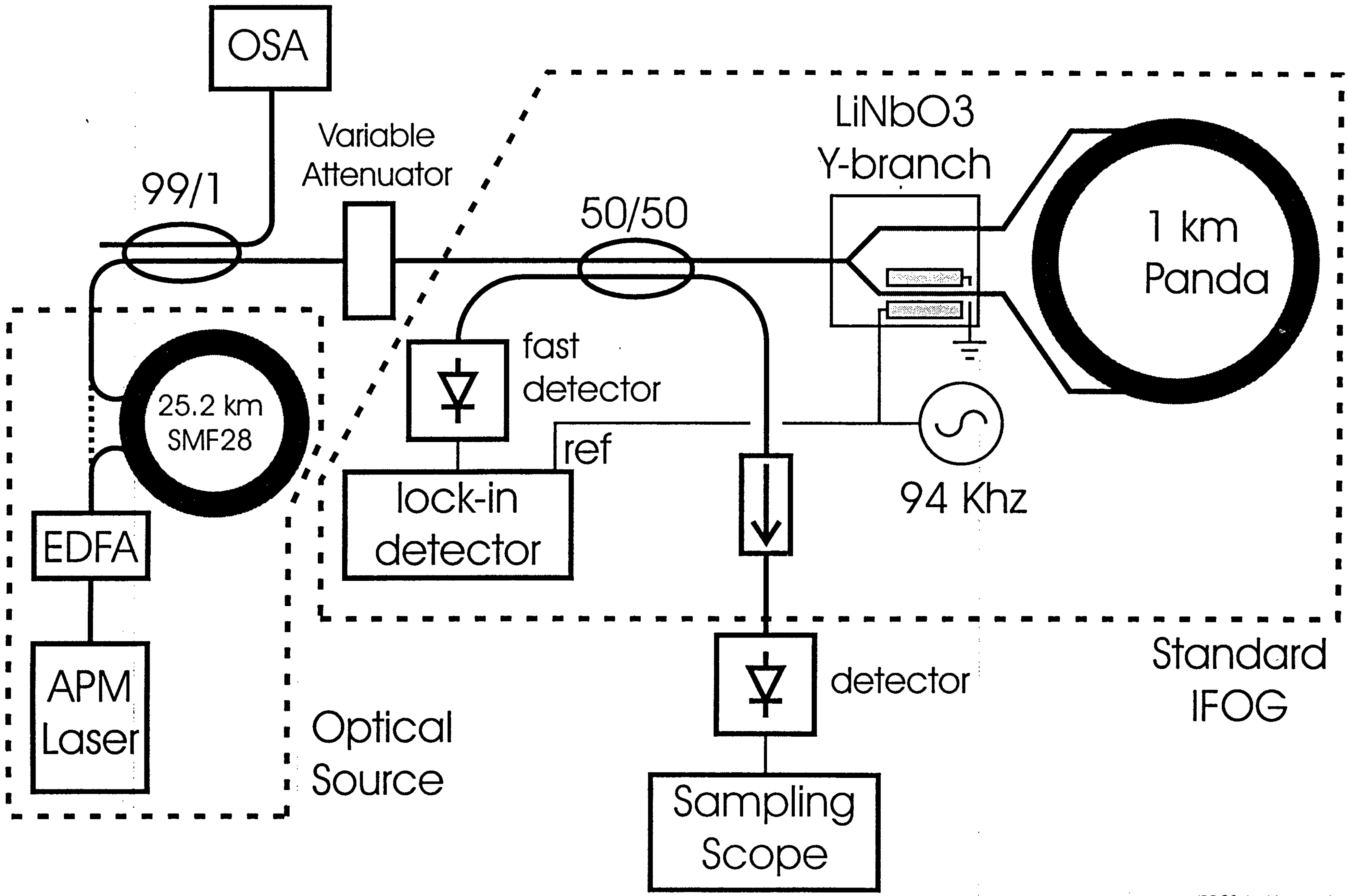
[3] S. Ezekiel and H. J. Arditty, "Fiber-Optic Rotation Sensors," *Fiber-Optic Rotation Sensors and Related Technologies*, pp.2-26, 1982.

[4] K. Tamura, E. Yoshida, T. Sugawa, and M. Nakazawa, "Broadband light generation by femtosecond pulse amplification with stimulated Raman scattering in a high-power erbium-doped fiber amplifier," *Optics Letters*, vol. 20, no. 15, p. 1631-3, 1995.

Figure Captions

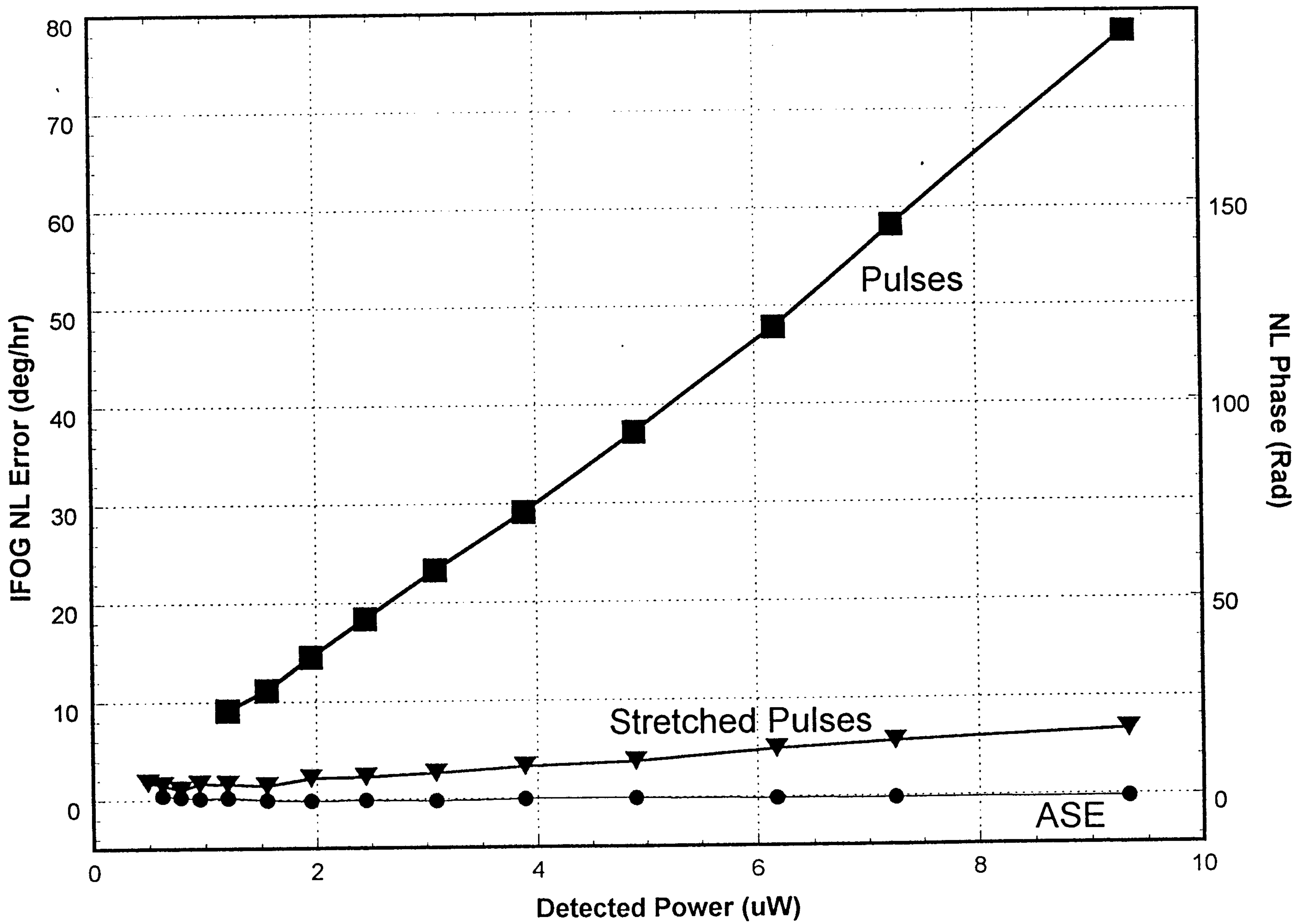
Figure 1. Experimental setup of the pulse excited IFOG. The pulse stretcher is removable and the EDFA can act as an ASE source.

Figure 2. Comparison of power dependent phase error for short pulse, stretched pulse, and ASE excitation of the IFOG.



IFOGSetupMemo.cdr

Power Dependent IFOG Error
Due to Kerr Nonlinearity



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